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# Mechanical Response of Porous Copper Manufactured by Lost Carbonate Sintering Process

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**Abstract.** This paper investigated the mechanical response of porous copper manufactured by LCS under three-point bending and Charpy impact conditions. The effects of the compaction pressure and $K_2CO_3$ particle size used in producing the porous copper samples and the relative density of the samples were studied. The apparent modulus, flexural strength and energy absorption capacity in three-point bending tests increased exponentially with increasing relative density. The impact strength was not markedly sensitive to relative density and had values within 7 – 9 kJ/m$^2$ for the relative densities in the range 0.17 – 0.31. The amount of energy absorbed by a porous copper sample in the impact test was much higher than that absorbed in the three-point bending test, impling that loading strain rate had a significant effect on the deformation mechanisms. Increasing compaction pressure and increasing $K_2CO_3$ particle size resulted in significant increases in the flexural strength and the bending energy absorption capacity, both owing to the reduced sintering defects.

## Introduction

Porous metals or metal foams have attracted a lot of interests both in academia and industry because of their exceptional mechanical and physical properties and many potential applications in light-weight structures, energy absorption, thermal management, sound absorption and electromagnetic shielding [1-6]. There is currently a range of technologies available or in development for manufacturing porous metals. Porous metals with low-melting-point metal matrices are normally manufactured by liquid or semi-liquid foaming technologies, and are generally termed metal foams. Porous structures of high-melting-point metals and alloys are often manufactured by solid route methods. The Lost Carbonate Sintering (LCS) process is one of the solid route technologies for manufacturing open-cell porous metals with controlled pore structures [7]. LCS is a simple, low cost process with a good control over pore size and porosity and suitable for a range of metals that can be easily sintered.

This paper investigates the mechanical response of porous copper manufactured by LCS under three-point bending and Charpy impact conditions. The effects of compaction pressure, $K_2CO_3$ particle size and the resultant relative density on the apparent modulus, flexural strength, bending energy absorption capacity and impact strength of the porous copper samples are studied.

## Experimental

The general procedure of LCS process was described in [7]. In LCS, a metal powder and a carbonate powder are mixed at a given volume ratio. The powder mixture is compacted and then sintered. A porous metal part is finally obtained by removing the carbonate particles from the sintered compact either by decomposition or by dissolution. The raw materials used in this study were commercially pure copper and potassium carbonate ($K_2CO_3$) powders supplied by Ecka Granules (UK) Ltd and E&E Ltd, respectively. The Cu powder consisted of spherical particles with particle diameters below 75 μm. The $K_2CO_3$ powders consisted of granular particles with two different size ranges of 710 – 1000 μm and 2000 – 3000 μm. The volume fraction of copper in the copper-$K_2CO_3$ mixture was 0.2, 0.25, 0.3, 0.35 or 0.4, giving the resulting porous copper a relative density of 0.17, 0.21, 0.24, 0.27 or 0.31. The compaction pressure was either 140 MPa or 210 MPa. The sintering temperature was 850 °C and the sintering time 4 hrs. The $K_2CO_3$ particles in the sintered compacts were removed by the dissolution route.

The three point bending tests of the porous copper samples were carried out on an Instron 4200 mechanical tester at a crosshead speed of 1 mm/min. The samples for the three-point bending tests were approximately 40 mm long, 15 mm wide and 10 mm thick. The span between the two supporting points was set as 36 mm. The Charpy impact tests of the porous copper samples were carried out on a Zwick impact machine using a pendulum set at a potential energy of 0.98 J. The samples for the impact tests were approximately 40 mm long, 10 mm wide and 10 mm thick, without any notches.

The apparent modulus of linear deformation and flexural strength of the porous copper samples were obtained from the three-point bending tests in accordance with AMST standard E855 and were calculated by [8]:

$$E = \frac{PL^3}{4bh^2\delta} \quad \sigma = \frac{3FL}{2bh^2} \tag{1}$$

where $b$ is the width of the test sample, $h$ is the thickness, $L$ is the span length between the two supports, $P$ is a load increment when the sample is in the linear deformation region, $\delta$ is the deflection increment at middle span corresponding to the load increment $P$, and $F$ is the maximum load corresponding to the break of the sample. In this experiment, $L$ = 36 mm, $b$ = 15 mm and $h$ = 10 mm.

**Results and Discussion**

Figure 1 shows the load-displacement curves of the porous copper samples with the same pore sizes of 710-1000 μm but with different relative densities in the three-point bending tests. The compaction pressure used in manufacturing these samples was 140 MPa. In each curve, the load increased nearly linearly with displacement when the displacement was small. With increasing displacement further, the load still increased but the gradient of increase decreased gradually. The load reached a maximum when the underside of the porous copper sample started to crack during the bending. The load then decreased with increasing displacement as the crack propagated to fracture.

Figure 2 shows the apparent modulus of linear deformation of the porous copper samples as a function of relative density. The apparent modulus was calculated by Equation (1) based on the apparently linear region of the load-displacement curve. It should be pointed out that this region of

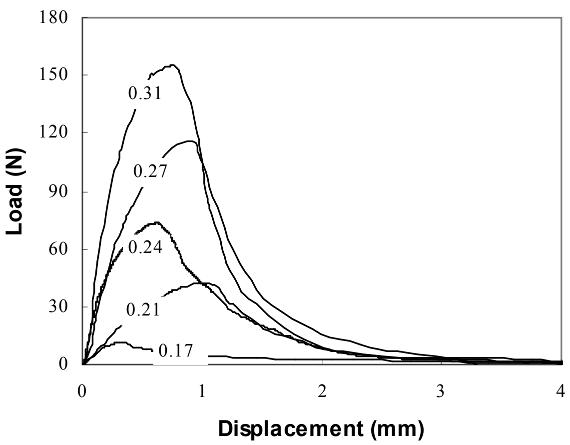


Figure 1 Load-displacement curves of the porous copper samples with different relative densities under three point bending

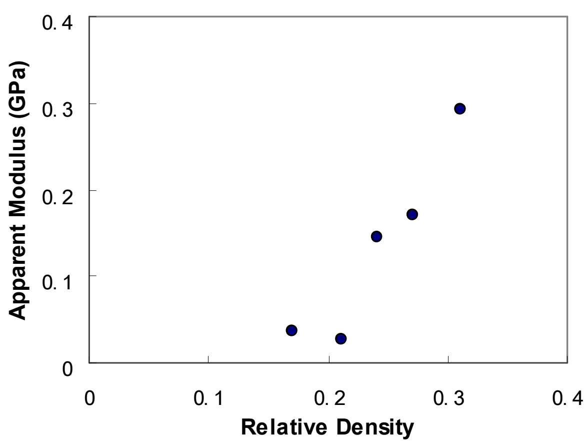


Figure 2 Variation of apparent modulus of linear deformation with relative density

the curve was neither exactly linear nor elastic. Some plastic deformation already took place in this region. The apparent modulus was lower than the Young's modulus of the porous copper sample. Figure 2 shows that the apparent modulus increased rapidly with increasing relative density. This was consistent with the behaviour of the conventional metal foams documented in the literature, where the relationships between the relative modulus of elasticity and relative density followed the power law [1].

Figure 3 shows the flexural strength of the porous copper samples as a function of relative density. The flexural strength was the maximum stress at which the sample fractured at the underside. The flexural strength increased rapidly with increasing relative density. Again, this was consistent with the behaviour of the conventional metal foams documented in the literature, where the relationships between the flexural strength and relative density followed the power law [1].

Figure 4(a) shows the impact strength of the porous copper samples as a function of relative density. The impact strength of a porous copper sample was the amount of energy absorbed by the sample in the Charpy impact test divided by its cross-sectional area. For comparison, Figure 4(b) shows the bending energy absorption capacity as a function of relative density. The bending energy absorption capacity of a porous copper sample was expressed in terms of the amount of energy absorbed by the sample in the three-point bending test divided by its cross-sectional area. The amount of energy absorbed in the bending test of a porous copper sample was the area underneath the load-displacement curve as shown in Figure 1, which was determined by integrating load with respect to displacement.

Figure 4 shows that the bending energy absorption capacity increased rapidly with increasing relative density while the impact strength was not markedly sensitive to relative density in the limited range (0.17 – 0.31) studied in this paper. The impact strength was much higher than the bending energy absorption capacity. With the relative density in the range 0.17 – 0.31, the former was 7 – 9 kJ/m$^2$ and the latter was only 0.1 – 1.2 kJ/m$^2$. In other words, the amount of energy absorbed by a porous copper sample in the impact test was much higher than that absorbed in the three-point

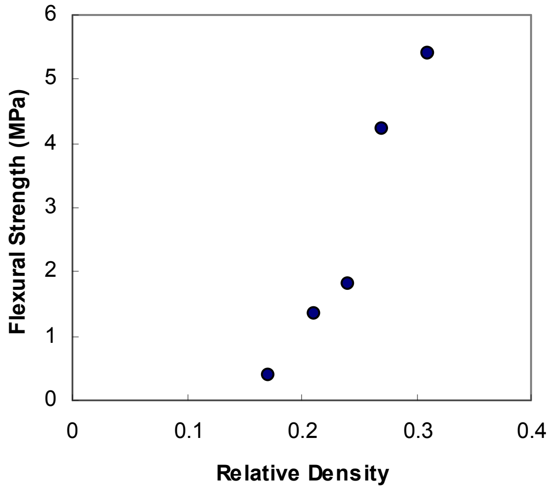


Figure 3 Variation of flexural strength with relative density

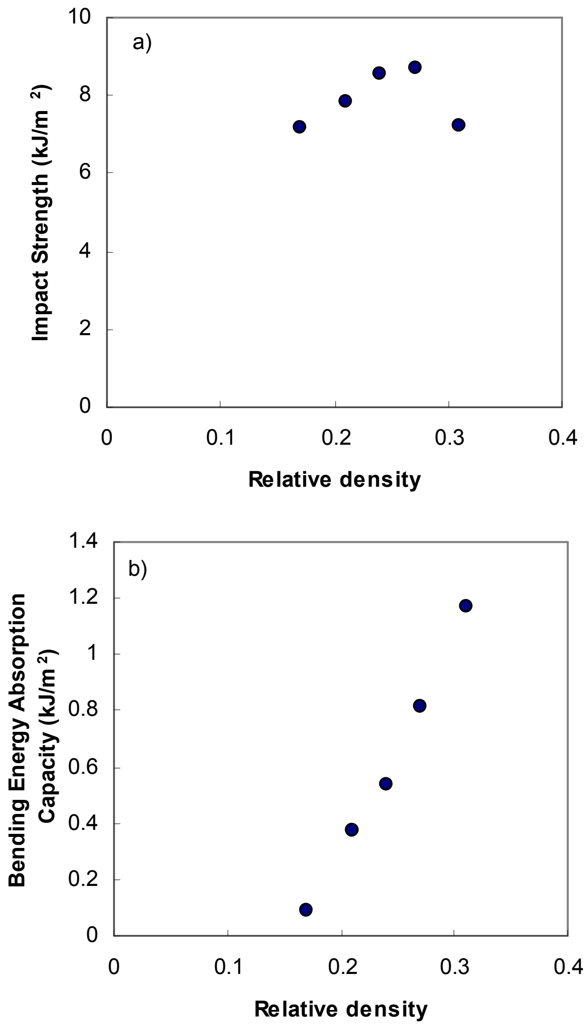


Figure 4 Variations of (a) impact strength and (b) bending energy absorption capacity with relative density

bending test. The loading conditions of the two tests were similar except that one was dynamic and the other was quasi static. It implied that the loading speed or strain rate had a significant effect on the deformation mechanisms and thus energy absorption capacity. The same phenomenon was also found in other porous metals manufactured by LCS. However, the deformation mechanisms are not well understood yet.

The preliminary investigations showed that the compaction pressure and the particle size of the $K_2CO_3$ powder used in producing the porous copper samples also had an influence on the three-point bending properties. Table 1 lists the flexural strength and bending energy absorption capacity of three porous copper samples with the same relative density of 0.24 but either different compaction pressures or different $K_2CO_3$ particle sizes.

Table 1 Effects of compaction pressure and $K_2CO_3$ particle size on flexural strength and energy absorption capacity

| Sample | Compaction Pressure (MPa) | $K_2CO_3$ Particle Size (μm) | Flexural Strength (MPa) | Bending Energy Absorption (kJ/m$^2$) |
|---|---|---|---|---|
| A | 140 | 710 – 1000 | 1.8 | 0.5 |
| B | 210 | 710 – 1000 | 3.9 | 1.0 |
| C | 140 | 2000 – 3000 | 3.4 | 0.9 |

Comparing Samples A and B showed that increasing compaction pressure from 140 MPa to 210 MPa resulted in significant increases in the flexural strength and the bending energy absorption capacity of the porous copper, both of which approximately doubled in values. The increases were owing to the enhancement of sintering by the higher compaction pressure. In the compaction process, pressing the powder mixture reduced the pre-sintering porosity and increased the contact areas between the neighbouring copper particles. During the subsequent sintering process, cohesion took place between the copper particles as necks grew at the points of particle contact. A higher compaction pressure would generally result in larger neck sizes between the particles and thus a stronger porous metal. However, the neck size does not increase linearly with the compaction pressure [9]. It was found in the sintering of copper powders that the increment of neck size was very rapid when the compaction pressure increased from 0 to 200 MPa, but was very limited when the compaction pressure kept increasing from 200 MPa to 600 MPa [9]. In the compaction stage of LCS for manufacturing porous copper, it is desirable to adopt a compaction pressure in the region of 200 MPa.

Comparing Samples A and C showed that increasing $K_2CO_3$ particle size from 710 – 1000 μm to 2000 – 3000 μm resulted in significant increases in the flexural strength and the bending energy absorption capacity of the porous copper. The change in the mechanical properties of the porous copper samples was not considered owing to the change in pore size itself. Instead, the change in the mechanical properties was very likely owing to the change in the amount of sintering defects characteristic of the LCS process. The mechanical properties of the porous metal depend on the integrity of its cell walls, which in turn depends on the particle size ratio between the metal and $K_2CO_3$ powders. In LCS, the metal particles should be significantly smaller than the $K_2CO_3$ particles in order to fill in the interstices between the $K_2CO_3$ particles [7]. For a given metal powder, the degree of filling is affected by the $K_2CO_3$ particle size. For larger $K_2CO_3$ particles, the interstices between them are larger and therefore easier to be filled. The sintering of these particles would lead to stronger cell walls of the resultant porous metal. For smaller $K_2CO_3$ particles, however, the interstices between them are smaller and it is more difficult for them to be filled completely. In the narrow parts of the network of interstices, the metal particles may be disconnected with each other. As a consequence, the cell walls of the resultant porous metal have more defects and thus weaker. The flexural strength and the associated bending energy absorption capacity are thus lowered. This size-difference effect should become insignificant when the $K_2CO_3$-metal particle size ratio becomes greater than 5.

## Conclusions

The apparent modulus, flexural strength and energy absorption capacity of the porous copper manufactured by LCS in three-point bending tests increased exponentially with increasing relative density in the range 0.17 – 0.31. The impact strength of the porous copper was much higher than the bending energy absorption capacity. It was not markedly sensitive to relative density and had values within 7 – 9 kJ/m$^2$ for the relative densities in the range 0.17 – 0.31. Increasing compaction pressure from 140 MPa to 210 MPa and increasing $K_2CO_3$ particle size from 710 – 1000 μm to 2000 – 3000 μm in producing the porous copper samples resulted in significant increases in the flexural strength and the bending energy absorption capacity, both owing to the reduced sintering defects.

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